NASA-CR-203788

7N-47-CR

021666

Large Scale Forcing of Middle and Upper Level Clouds: Preliminary Results from a FIRE Cirrus Case Study

Gerald G. Mace and Thomas P. Ackerman

Department of Meteorology
The Pennsylvania State University
University Park, PA 16801

1. Introduction

In recent years, a major goal of atmospheric research has been directed toward understanding the role clouds play in the global climate system. Numerous published papers have pointed to the fact that clouds significantly impact the global climate system. However, the magnitude and even the sign of the impact which clouds exert is, however, still a subject of scientific debate. Cess et al. (1990) concluded that the major source of disparity in the sensitivity of 17 GCM simulations forced by a common climate perturbation rested almost entirely on the way in which clouds were parameterized in the models.

Cirrus clouds, in particular, represent a unique challenge in the parameterization problem. The large scale dynamical forcing of cirrus cloud systems tends to be complicated by the dynamical structure of the upper troposphere. The present knowledge of upper tropospheric dynamics has been largely determined from highly idealized models with little observational verification (Keyser and Shapiro, 1986). This deficiency in observational evidence results in a lack of knowledge in the relationship between the cirrus clouds and the environment in which they exist. This environment is characterized by small water vapor concentrations in which vertical motions are forced by small imbalances in the large scale atmospheric flow. It is necessary, therefore, to acquire thermodynamic and dynamic observations of high precision to adequately resolve the relevant mechanisms which lead to cirrus cloud development. Furthermore, the microphysical properties of the cirrus, which in turn govern its radiative impacts are strongly coupled to the dynamical and thermodynamical fields. The presence of the cirrus itself, however, alters these fields through radiative heating and vapor condensation. It is precisely this coupling between large-scale environment and small scale cloud properties that must be diagnosed if the parameterization problem it to be solved.

This connection between scales is one of the reasons the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE Cirrus II) was conducted in Coffeyville, Kansas in November and December, 1991. This location was chosen, in large part, because of the presence of the NOAA wind profiler demonstration array. These 404 Mhz wind profilers were located in a mesoscale array around Coffeyville (Fig. 1) and provided continuous horizontal and vertical wind information at high temporal resolution from approximately 1 Km above mean sea level (msl) to 16 Km msl with vertical resolution ranging from 250 m to 900 m. This data was supplemented by spatially and temporally enhanced radiosonde information. Consequently, the mesoscale characteristics of the cirrus environment were characterized quite well. A dataset of unprecedented resolution and detail was obtained by combining this information with detailed microphysical and radiative measurements from both surface based and aircraft based sensors.

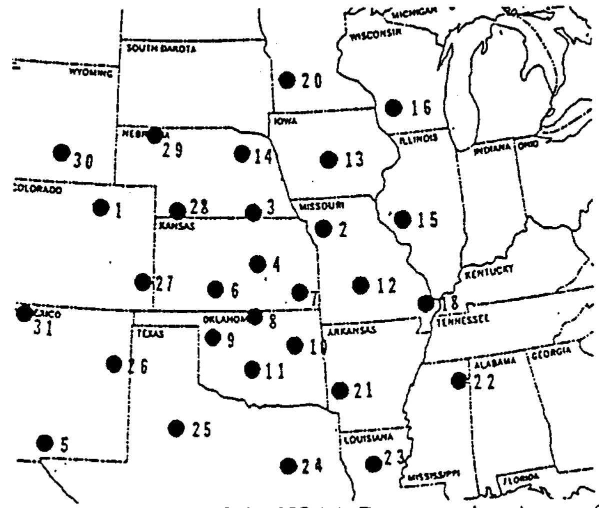

Fig 1. A portion of the NOAA Demonstration Array of 404 Mhz wind profilers. The sites used in the calculations presented in the text were 8, 9, 6, 4, 7, and 10.

This dataset will be exploited to present preliminary results from one case study conducted during FIRE Cirrus II, concentrating mainly on the mesoscale dynamical forcing of the upper cloud system.

2. Diagnostic Methods

Zamora et al. (1987) presented a method whereby the linear kinematic properties of the atmospheric flow could be determined from three non-colinear wind profiler observations. They noted that the primary drawback of their method was that it required the wind field to vary in a linear fashion. Nonlinear variations in the flow would then lead to erroneous results. The method outlined here takes advantage of the number of wind profilers in the region and is a logical extension of the method described by Zamora et al. (1987).

By using a second order Taylor Series expansion in two dimensions, a scalar variable, $\alpha(x,y)$, can be expanded about a point in space, (x_0, y_0),

$$\alpha(x,y) = \alpha_0 + \frac{\partial\alpha}{\partial x}\delta x + \frac{\partial\alpha}{\partial y}\delta y + \frac{\partial^2\alpha}{\partial x^2}\frac{\delta x^2}{2} + \frac{\partial^2\alpha}{\partial x\partial y}\frac{\delta x\delta y}{2} + \frac{\partial^2\alpha}{\partial y^2}\frac{\delta y^2}{2} \tag{1}$$

Here the LHS is a measured quantity at a profiler location denoted by (x, y). The point (x_0, y_0) is the location to which we would like to interpolate the observed values. The distance constants on the RHS are determined by the location to which we are interpolating and the geometry of the observational network. Our goal is to determine the value of α as well as the first and second order differentials at the point (x_0, y_0). Solving for these six unknowns requires six independent measurements of α. If these observations exist, then the six unknowns can be written as the vector,

$$\mathbf{D} = \left(\alpha(x_0, y_0), \frac{\partial\alpha}{\partial x}, \frac{\partial\alpha}{\partial y}, \frac{\partial^2\alpha}{\partial x^2}, \frac{\partial^2\alpha}{\partial x\partial y}, \frac{\partial^2\alpha}{\partial y^2}\right) \tag{2}$$

The observations on the LHS can be expressed as the vector,

$$\mathbf{U} = (\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6) \tag{3}$$

and the system of equations can be written

$$\mathbf{DX=U} \tag{4}$$

where $\mathbf{X}$ is the 6x6 matrix of distance constants. Calculation of the kinematic properties of the variable α then reduces to solving the linear system for the vector $\mathbf{D}$.

When Eq 4 is solved successively for orthogonal wind components, the method permits the calculation of quantities such as the horizontal divergence, the vertical component of vorticity and the deformation properties of the atmospheric flow. In addition to being more accurate due to its higher order determination, expanding the series out to second order allows the determination of spatial cross sections of the differential quantities and the variables which depend on them, such as vertical velocity and ageostrophic wind. It is then possible to examine the forcing of the three-dimensional vertical circulations by the large scale flow using methods developed to diagnose frontal circulations (e.g., Keyser and Shapiro (1987)). Time height cross sections of the applicable variables can also be interpolated directly to Coffeyville for a direct correlation of the large scale forcing with the observed cirrus cloud properties.

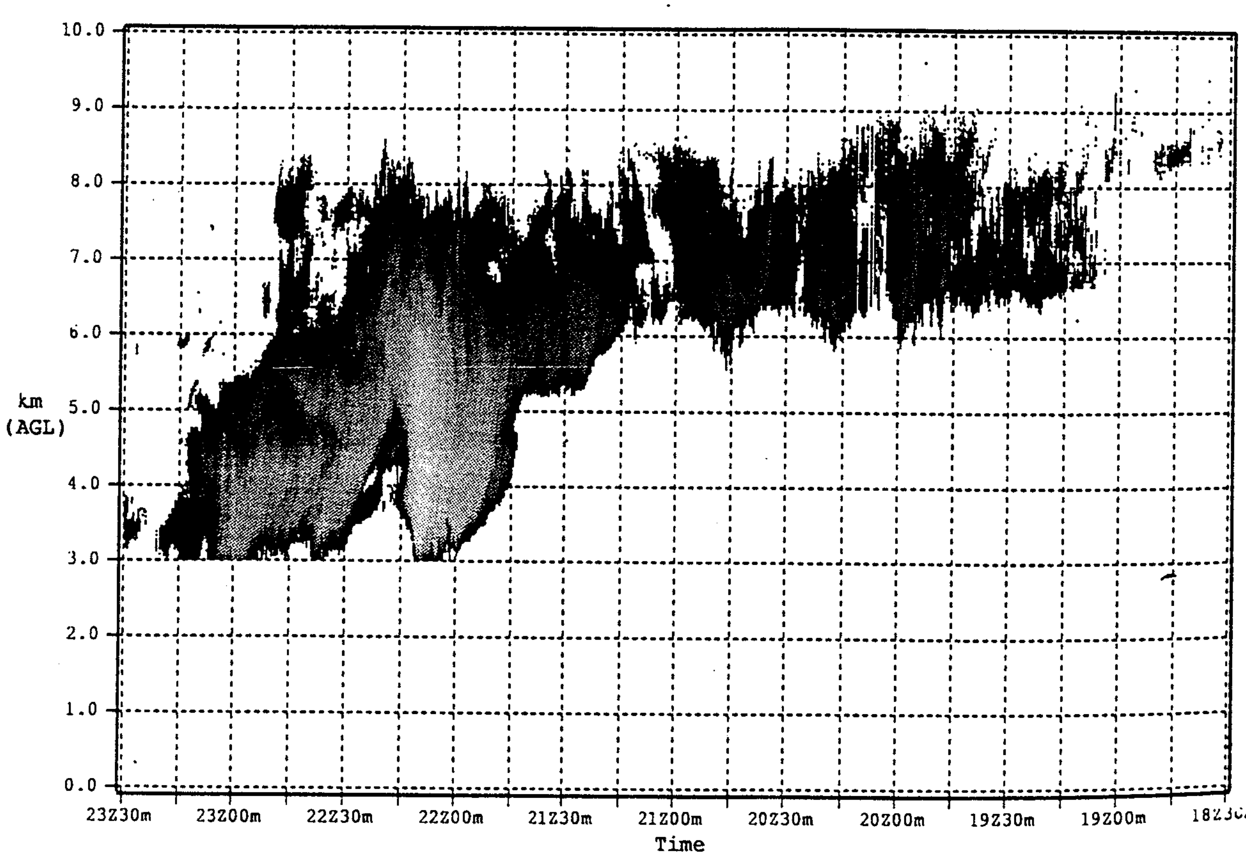

Fig. 2. Time height series of uncorrected reflectivities measured by the Penn State 94 Ghz cloud Radar. Note time increases from right to left.

3. Case Study

During the afternoon of 26 November, 1991, a small amplitude trough axis was moving slowly eastward over the central United States. The surface analysis revealed a low pressure center in northwestern Nebraska with a trough of low pressure extending into central Kansas. Associated with this trough of low pressure was a north-south band of cloudiness. This band gives the appearance of being associated with a warm front, although surface reports indicate the band contained mainly non-precipitating middle and upper-level clouds.

Tenuous cirrus clouds at a height of 8.5 Km were first observed over Coffeyville at 1830z. Soundings from the surrounding region indicated a continual moistening of the upper troposphere during the late morning hours. Fig. 2 shows a time-height cross section of radar reflectivities observed with the Penn State 94 Ghz cloud radar (Peters et al., this issue). As can be seen from this figure, cloud base quickly lowered to 7.25 Km and the layer thickened with tops extending to near 9 Km. The reflectivity pattern indicates convective instability within this layer. Fig 3 shows the 2025z sounding over Coffeyville. This profile clearly shows the moist layer associated with the cirrus deck just below 7 Km. The cloud tops were well below the tropopause, which was located at 10.25 Km. The dew point profile does not show a well defined cloud top.

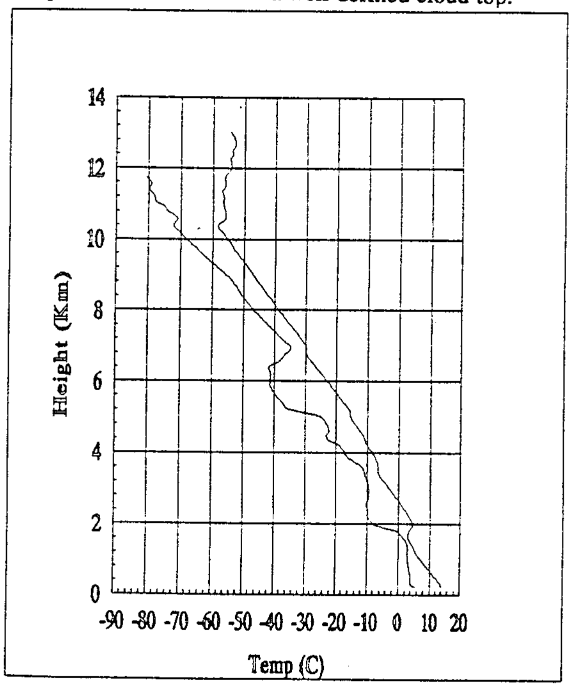

Fig 3. Radiosonde profile recorded at Coffeyville, Kansas. Instrument was launched at 2025z, 26 Nov, 1991.

The cloud deck remained nearly continuous until 2115z when a significant lowering of the cloud base was observed. By 2200z, cloud base was near 3 Km and cloud top extended to 8 Km. Enhanced reflectivities were observed after this time as the cloud developed a more mid-level appearance. By 2300z, cloud top had lowered rapidly to near 5.25 Km and nearly complete dissipation of the deck occurred by 2330z.

The forcing of the large scale vertical motions can be seen in Fig. 4. This figure shows divergence values interpolated to Coffeyville using the six wind profilers indicated in Fig 1.

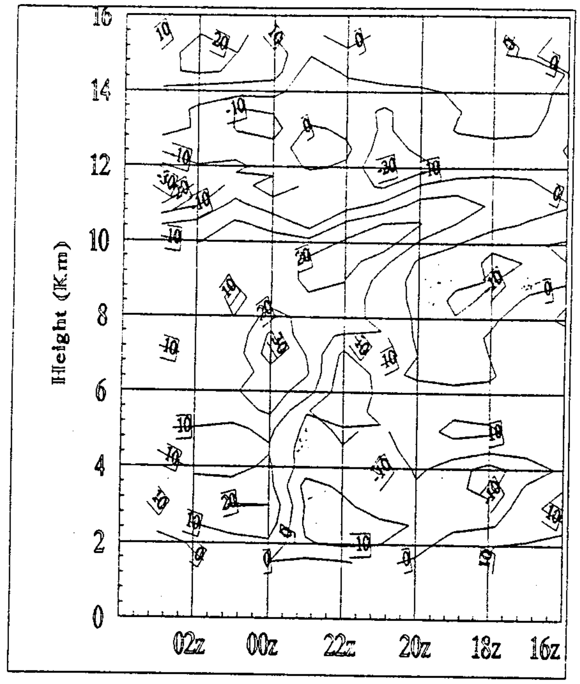

Fig. 4 Divergence values in units of 10^{-5} s^{-1} interpolated to Coffeyville using the method described above. Values of convergence are shaded. Note that time increases from right to left.

The most prominent feature of this profile is the region of upper level divergence which first appeared at 1800z at 11 Km. This divergent layer appeared to strengthen and deepen with the main axis of divergence descending with time. Coupled with this layer of divergence were two layers of convergence. A convergent layer first appeared over Coffeyville at 10z, 26 November and remained at 9 Km throughout the morning hours. Of particular interest is the manner in which upper level clouds first appeared as the convergence-divergence couplet organized over the site. The layer of upper convergence vanished over Coffeyville by 2000z. Vertical motions then appeared to be forced by the lower convergent layer between 2 and 4 Km. This layer reached its maximum intensity near the time of the lowering of cloud based mentioned earlier. This lower convergent layer decreased in intensity and became divergent by 0000z, 27 November. This is in line with the dissipation of the cloud layer and the passage of an upper level trough. It then appears that subsidence was initiated due to the strong convergent layer above 10 Km.

Mesoscale vertical motions were determined using the hourly averaged profiler measured vertical velocities at the six sites. These values were then interpolated to Coffeyville using the method described above. Problems are known to exist with profiler vertical beam measurements due to contamination by any small off zenith component in the beams. Under light wind conditions,

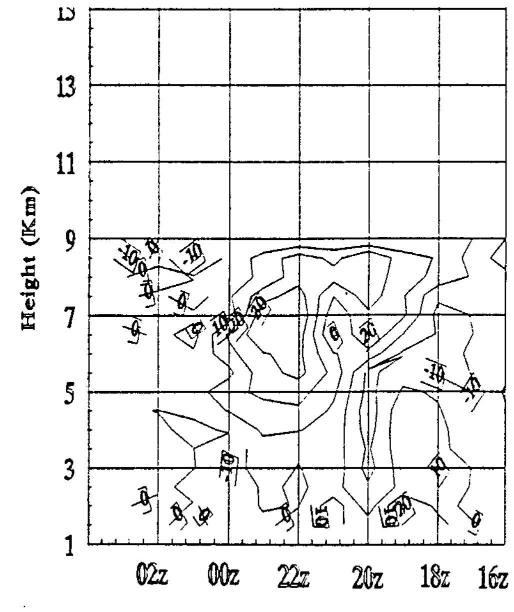

Fig. 5 Observed vertical velocities in units of cm s^{-1}. Data was available only to 9 Km.

contamination of the vertical beam measurements by the horizontal wind should be minimized. Wind speeds at cloud level generally remained less than 20 ms^{-1} during the afternoon of 26 November. Absolute accuracy is not claimed here, however by comparing the vertical velocity with the divergence and cloud patterns it would appear that the measurements are qualitatively correct. Significant upward motion appeared in conjunction with the upper convergence-divergence couplet mentioned above. This layer of upward motion deepened and descended and reached its maximum value at the same time as the maximum refelctivities were measured over Coffeyville. The significant uplift ceases with the trough passage at 0000z, 27 Nov and correlates well with the dissipation of cloudiness over Coffeyville.

4. Summary

The discussion presented above represents an initial analysis of the large scale forcing of the cirrus clouds observed during this particular case study. It appears that the vertical motions which contributed to upper cloud formation, maintenance and dissipation were the result of varying influences throughout the troposphere. Of significance is the appearance that the middle and upper tropospheric clouds were initially forced by features which resided above 8 Km but eventually were maintained by the coupling of middle and lower tropospheric convergence. Dissipation was initiated after the upper trough passage when strong convergence was initiated near the tropopause.

While this type of analysis is illuminating, it does not necessarily help solve the parameterization problem. Since upper cloud formation is closely coupled with small changes in water vapor concentration, this factor needs to be examined closely. Additionally, the mesoscale vertical motions can be visualized as the result of imbalances in the larger scale flow pattern. Identifying these imbalances and then diagnosing the resulting vertical circulations on regional scales will be necessary to carry forward the linkage of cirrus cloud formation with large scale forcing. It will then be necessary to test the ability of meso and larger scale models to accurately model the imbalances in the wind and thermal fields which are important to cirrus cloud formation and maintenance. This is the direction future research will take.

Acknowledgments: We are indebted to R. Peters, S. Williams, R. Thompson and T. Treaster for their invaluable assistance with the intrument development and data collection. This research was supported under NASA Grant NAG-1-1095 and DOE ARM Grant DE-FG02-90ER61071

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